Biomorphic Systems based on Smart Actuators

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ABSTRACT

A comparative review of actuation technologies is presented. Innovative mechanism ideas that combine high force and deflection are described. Flexible smart actuators are obtained utilizing real time adaptive bio-morphic controls. Such flexible smart actuators constitute an enabling technology for a variety of biomorphic systems ranging from small, agile biomorphic explorers that emulate biological mobility to much larger humanoid or anthropomorphic system. Due to their potential ability to explore difficult, hard-to-reach terrain, bio-morphic explorers are promising for a variety of applications in law enforcement, hazardous environment inspection, toxic waste avoidance/ elimination, and search/rescue in disaster areas such as earthquake sites. The control mechanisms used for the actuators are based on biological principles. For example, a neurally inspired controller (with the Banked Stimulus-Response, BSR, control generated using a genetic algorithm) provides a mapping between the current state of the robot (measured by sense variables such as internal actuator angles, velocity, and internal periodic clocks) and a target internal configuration (configuration of internal actuator angles). Innovative foldable advanced mobility mechanisms in combination with multipod techniques inspired by peristalsis in an earthworm robot are described. Flexible actuators offer the versatility of both shape control as well as mobility attribute control.

1. INTRODUCTION AND BACKGROUND

Sojourner's success on the surface of Mars has proven beyond doubt that a *mobile* platform on a planetary surface, equipped with sensors, provides a wealth of new science data. Ideal for taking numerous panoramic pictures, the rover by itself could, however, "probe" chemical composition of only a limited number of rocks during its first month on the surface. In-situ, autonomous exploration and science return from surfaces, subsurfaces, and environments would be substantially enhanced if a large number of small, inexpensive, and therefore dispensable, microexplorers[1] equipped with dedicated microsensors could be spread over the surface by a lander or a larger rover. Mimicking biology, such bio-morphic explorers may possess animal-like mobility/adaptability. Their potential low-cost and small size will make them ideal for hazardous site exploration/inspection/testing. Their dedicated sensing functions and maneuverability would be invaluable in scouting missions and sample acquisition from hard to reach places. Such bio-morphic explorers would very well complement the abilities of the larger and relatively expensive exploration modes (e.g. landers, rovers, and aerobots). Bio-morphic

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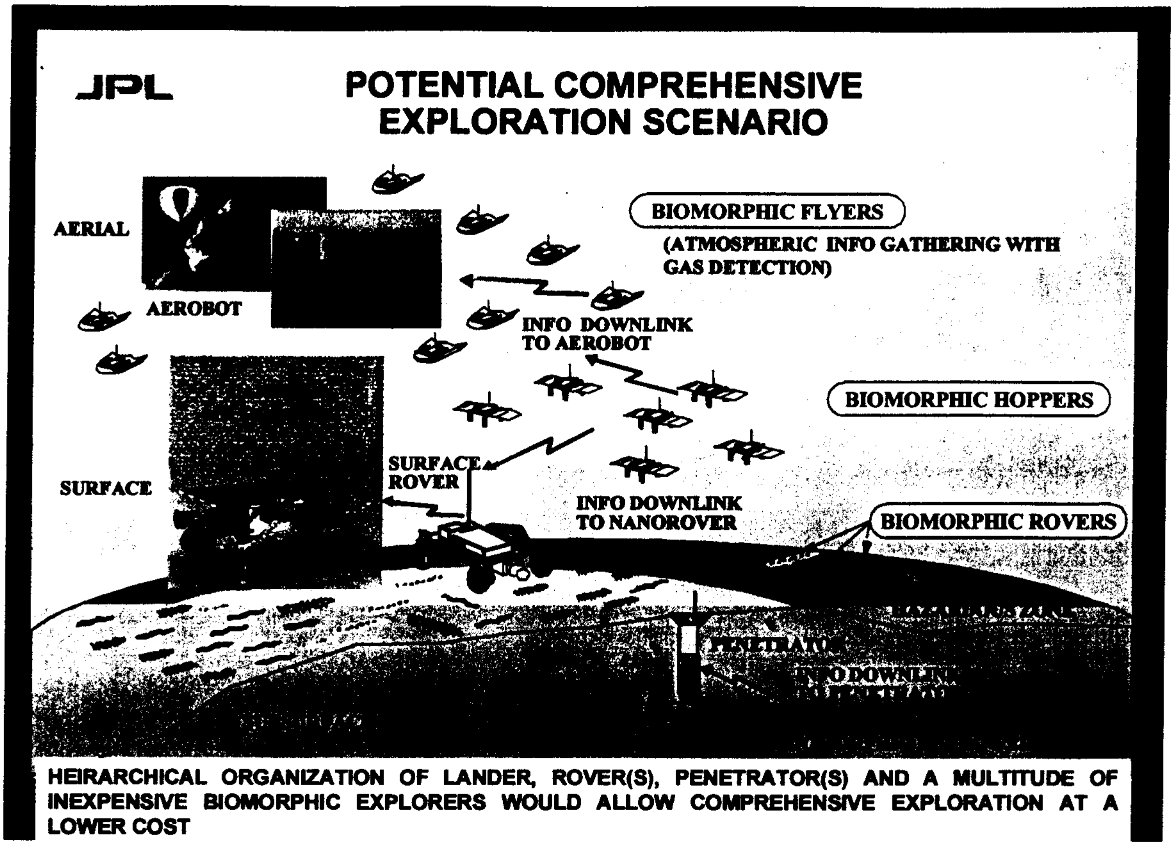

Figure 1:

explorers may possess varied mobility modes: surface-roving, burrowing, hopping, hovering, or flying, to accomplish surface, subsurface, and atmospheric exploration. Preprogrammed for a specific function, they could serve as "no-uplink, one-way communicating" beacons, spread over the exploration site, autonomously *looking for/at the object of interest*. In a hierarchical organization, these bio-morphic explorers would report to the next level of exploration mode (say, a large conventional rover) in the vicinity. This would allow a wide-spread and affordable exploration with a substantial amount of scouting for information about a new/hazardous area at lower cost and risk, combining a fast running rover to cover long distances and deploying numerous microexplorers for in-situ sensing and local sample analysis/acquisition. Figure 1 illustrates a potential comprehensive exploration scenario[1,2].

Microrobots and microrovers have attracted a great deal of research attention in recent years. Various combinations of wheeled and legged mobility mechanisms have been combined with a variety of sensors, power sources, navigation/control algorithms, and communication devices.

Realization of the vision of small expendable "terrain-traversing" explorers would require four key components: microsensors, power, advanced mobility, and communication. Multi-billion dollar commercial market forces already drive the development of three out of these four essential components (except the advanced mobility). For example: Each of the sensors for single, simple measurement such as temperature (thermistor), chemicals (e-nose), surface hardness (strain gauge), and wind (strain gauge) is typically quite small, and could be integrated as a part of an "antenna" and/or a "sting" of an insect-like explorer. On the other hand, microsensors such as microimagers are already being miniaturized to serve the growing digital imaging business for surveillance, security, science, and entertainment. Solid-state high power density batteries are advancing at a rapid pace, driven by the development in cellular phones, handheld computers, to long life watches, and other electronic gadgets. Low-power, limited range, low-bandwidth communication, adequate for the explorers, has also been addressed rather aggressively in recent years, to target the mass market of product ID tags and inventory control.

However, advanced mobility requires a "big leap" to make this vision possible. This paper presents a comparison of actuator technologies, particularly the potential of flexible actuators, their control using biomorphic algorithms, results of modeling, a logical architecture for controls and finally schematic principle of a eathworm like robot utilizing peristaltic motion.

2. BIO-MORPHIC EXPLORERS CONCEPT

Earlier work on biologically inspired robots using actuators as well as conventional motors has been done by Brooks[3], and many other workers internationally[4-15]. In our new paradigm[1,2,16,17], we combine "flexible" actuators and novel "bio-morphic" control, to capture key features and mobility attributes of animals. This takes us from the rigid, mobility-limited traditional robotics to adaptive, bio-morphic explorers. Coupled with biomorphic controls, the flexible actuators behave as smart actuators. The biomorphic systems so enabled can range all the way from insectoids to humanoids.

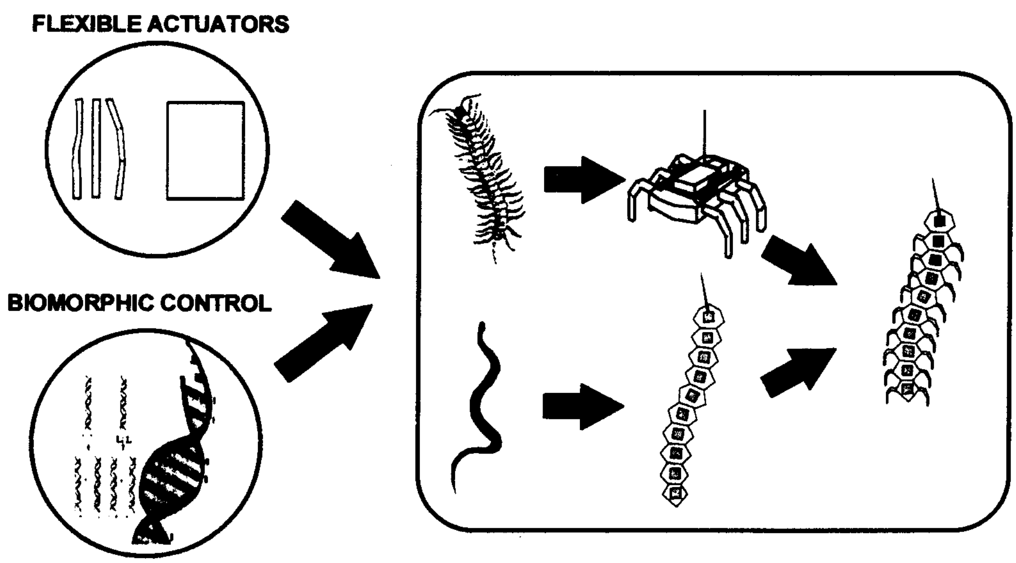

Figure 2: Advanced mobility for biomorphic explorers - lessons from biology

A. Advanced flexible actuators[16,17] will allow design of direct-driven limbs (legs/muscles/appendages) bypassing the need for complex chassis (motors and drive systems). The limbs will possess the added advantage of reconfigurability within a certain domain of mobile systems. For example, following are some of the possible explorer designs[1,2] that could be constructed using such flexible actuators:

i. Multipod[18] crawlers/burrowers for surface/subsurface exploration, maneuvering through soft soil and difficult terrain, adaptive to the environment (e.g. for Mars Exploration or hazardous area exploration such as chemical spill site or earthquake sites for dedicated sensing of specific targets).

ii. Jet propulsion[19] as in aquatic animals for navigation through fluids (e.g. for Europa Exploration[20] or marine/Navy applications)

iii. Hopping mechanisms for surface and aerial exploration

iv. Hovering mechanisms for aerial exploration

These options are illustrated in figure 3.

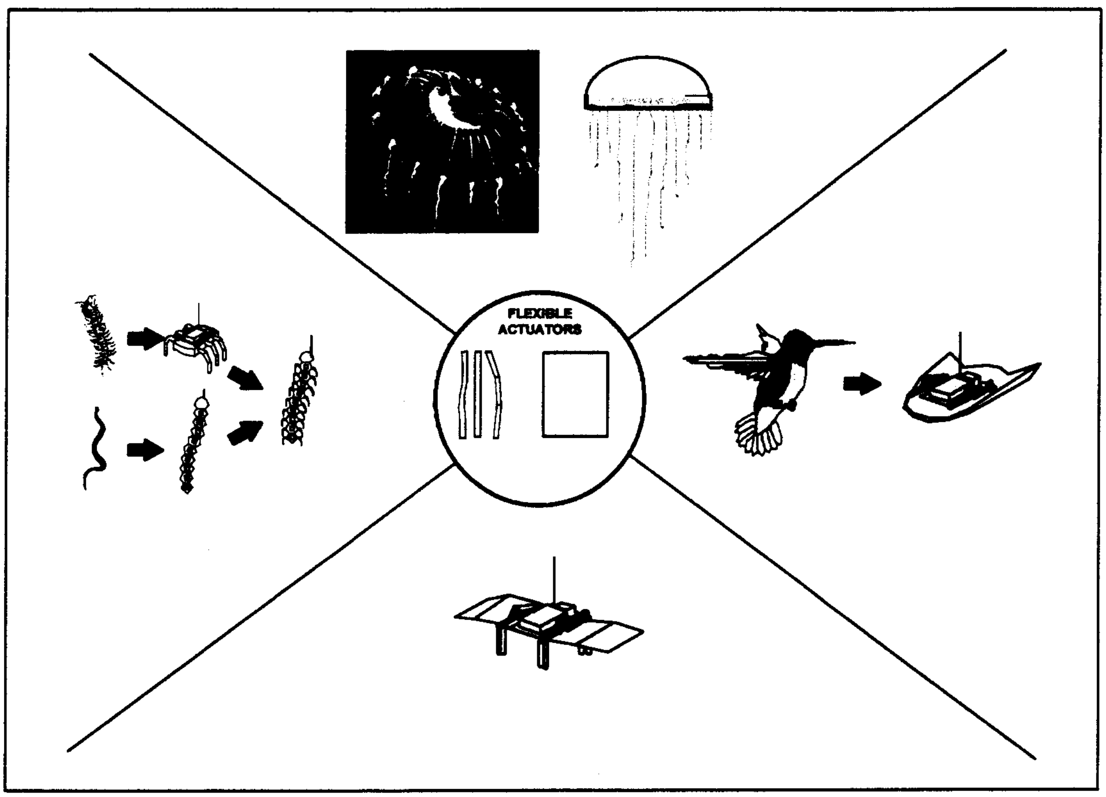

Figure 3: Advanced mobility for biomorphic explorers – possible implementations

B. Inspired from biology, bio-morphic controls (based on say, artificial neural networks implemented in low-power VLSI hardware) would be especially suited for controlling the inherently non-linear flexible actuators.

C. Revolutionary mechanisms for adaptation would replace traditional fixed designs. For example, sensor-triggered control sequence to the legs may be determined for optimal ways to move in various different environmental conditions.

D. Ultimately, cooperative behavior among many such explorers would enable new types of missions. Using groups of small, inexpensive bio-morphic explorers in conjunction with larger, traditional mobile robots will enable tasks, too complex for a single robot.

3. ADVANCED ACTUATOR COMPARISON

A survey[17] of emerging/advanced actuation technologies is summarized in Table 1. This comparison of course requires constant updating, as the field advancing at a rapid pace. **Selection/optimization of smart actuator material(s)** from the rapidly advancing knowledge-base of advanced composite materials and innovative amplification techniques with interesting/useful properties (e.g. combination of high force and displacement at low power), will lead to hardware-implementable designs for the bio-morphic explorer. Table 1 illustrates how piezoceramics are one of the leading candidate, **especially when dimensions shrink and approach those of thin films,** where properties are tailorable by fine composition control. Thin film growth techniques through their close control on composition allow a much finer control of hysterisis and aging properties. In particular, the lower holding power requirement by piezoceramics

Table 1: Comparison of Actuation Technologies

			POLYMERIC MATERIALS		
	PIEZOCERAMIC	SHAPE MEMORY ALLOY	PVDF and PVDF copolymers	Polymides PMMA Polyurethanes	MAGNETO-STRICTIVE
MECHANISM	PIEZOELECTRIC & ELECTROSTRICTIVE	THERMAL: MARTENSITIC → AUSTENITIC PHASE CHANGE	PIEZOELECTRIC, PHASE TRANSITION	ELECTRO-STRICTIVE	MAGNETIC FIELD INDUCED BY COIL
STRAIN	10^{-4} TO 0.3×10^{-2}	10^{-6} TO 10^{-1}	10^{-6} TO 10^{-1}	10^{-9} TO 10^{-1}	10^{-5} TO 10^{-2}
DISPLACEMENT	LOW TO HIGH	MEDIUM TO HIGH	LOW TO HIGH	LOW TO MEDIUM	MEDIUM
FORCE (In Newtons)	HIGH ~ 100-1000	MEDIUM ~ 1-10	SMALL	SMALL	HIGH
HYSTERISIS	TAILORABLE BY COMPOSITION	SMALL	LARGE	SMALL TO MEDIUM	LARGE
AGING	COMPOSITION DEPENDENT	VERY SMALL	LARGE	LARGE	SMALL
TEMPERATURE RANGE OF OPERATION	−196°C → 300°C WIDE	−196°C → 100°C WIDE	−50°C → 150°C MEDIUM	−10°C → 80°C LIMITED	-273°C → 100°C WIDE
RESPONSE SPEED	μsec-msec	seconds	μsec-msec	μsec-msec	μsec-msec
ACTIVATION MODE	BOTH OPTICAL AND ELECTRICAL	THERMAL AND ELECTRICAL	ELECTRICAL	ELECTRICAL	MAGNETIC
POWER REQUIREMENT	LOW	LOW to MEDIUM	MEDIUM	LOW TO MEDIUM	HIGH
RADIATION HARDNESS	YES	YES	TBD	TBD	YES
CYCLABILITY	EXCELLENT	GOOD	FAIR	FAIR–POOR	GOOD
PROSPECT OF MINIATURIZATION	GOOD	GOOD	GOOD	GOOD	FAIR

makes them attractive over magnetic actuators (which consequently suffer from the need for significant heat dissipation). With size reduction, the energy absorbed by piezoceramics could be up to two orders of magnitude higher[17,21] compared to electrostatic and magnetic actuators. This higher density is attributed to
the higher dielectric constant of the piezoceramics and the increasing breakdown field with reducing thickness[17,21]. Furthermore, piezoceramics offer the potential of solar driven, tetherless mechanisms since they can be actuated directly by optical illumination (350nm to 450nm) [22]. Piezoceramic actuation is potentially robust, amenable to low temperature operation, and intrinsically radiation-resistant. In addition, their ability to be batch-produced by thin film manufacturing techniques on large substrate areas offers convenience and cost effectiveness. Shape memory alloys offer many of these benefits too, except that they are relatively slow as the phenomenon is thermal in nature. However, their technology readiness for flexible actuator use is at a much higher level.

Innovations[17,22,23] based on advanced composite materials/flexible substrate-based flexible actuators, employing innovative amplification techniques to provide the desired combination of *high force and displacement characteristics* are being worked on to realize the building blocks of this new paradigm in mobility. The innovation options are summarized in Table 2.

Table 2: Challenges, Pay-off, and Key features of Innovation Options

MATERIAL INNOVATION	FABRICATION CHALLENGE	PAY-OFF	FEATURES ENHANCED
I Shape memory alloy wire, Piezoceramics	LOW	MEDIUM	HIGH FORCE, MEDIUM DEFLECTION WIDE TEMP RANGE OPERATION MEDIUM SPEED, ELECTRICALLY OPERATED
II Piezoceramics thin film/high temp. polymers	MEDIUM	MEDIUM	MEDIUM FORCE, HIGH DEFLECTION SCALEABLE, MEMS WIDE TEMP RANGE OPERATION MEDIUM SPEED, ELECTRICALLY OPERATED
III Optical Piezoceramics / high temp. polymers, polymeric actuators	HIGH	HIGH	HIGH FORCE& DEFLECTION COMBINATION, SCALEABLE, MEMS WIDE TEMP RANGE OPERATION HIGH SPEED, ELECTRICALLY & OPTICALLY OPERABLE

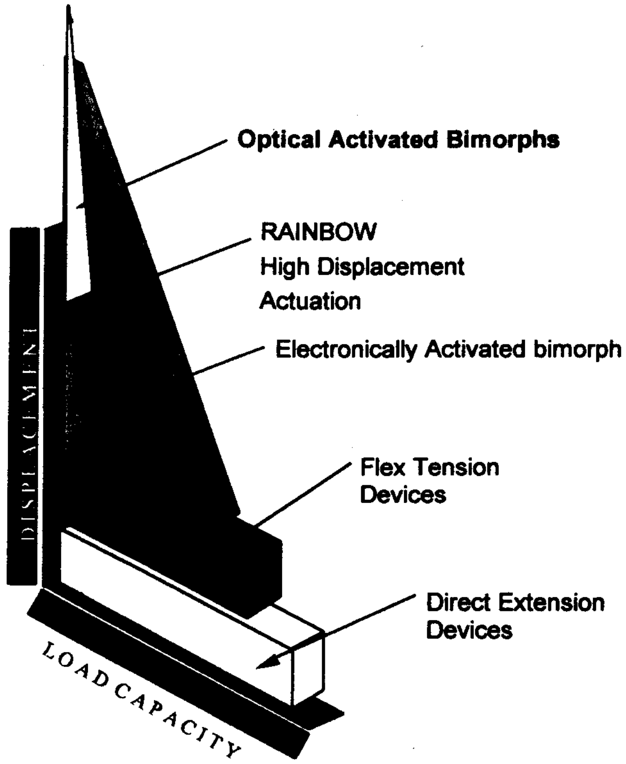

Figure 3

Figure 3 further shows the trade of load versus displacement for piezoceramics and their different amplification modes such as electrically/optically driven bimorphs, RAINBOWS[24] and flex-tensional amplification techniques. In fact, bimorph and flex-tensional elements can be combined to provide double amplification[25]. Optically driven bimorphs have a niche for applications requiring high displacement and low load requirement. Recent results on optical microactuation in piezoceramics are reported elsewhere[26].

4. CONTROL ALGORITHMS AND THEIR IMPLEMENTATION

Why Bio-morphic Controls Implemented on a Neural Network Chip?

The flexible actuators proposed are non-linear systems that are controlled most effectively by control mechanisms that allow adaptation of control sequence to determine its parameters while acting on the target environment as required. The recent emergence of neuro-reflexive control, a powerful paradigm that offers for the first time real-time adaptivity and learning ability with inherent fault tolerance, would make it possible to capture these attributes in an on-board, compact control hardware, not possible with conventional technology suite. Combining the flexible actuators and biomorphic controls would therefore offer for the first time a new direction in advanced mobility with new capabilities of adapting to terrain, enhanced spatial access owing to flexibility, scalability, and ease of multiplicity due to batch process amenable manufacturability. The Banked

Stimulus-Response (BSR) Control Algorithm[27,28,29] is expected to result in a complex multivariable transformation(s) matrix that would map the input (signals from a variety of strategically positioned sensors) on to the corresponding responses (actuator triggers for mobility, gait, and explorer configurations).

Logical Architecture for Bio-morphic Controls:

In biological systems, the control of periodic limb motion sequences are generally delegated to a lower level controller (e.g. spinal cord in humans) than the main CPU (e.g. the brain). This relieves the brain resources to attend to the higher level cognitive functions including sensory information processing (e.g. vision, hearing, etc.). This arrangement does not rule out a higher level command from the brain to the spinal cord to modulate/change the ongoing periodic motion whenever necessary based on sensory input received and processed. For example, decision to turn or run in a specific direction rather than walk in the sight of a prey/predator is executed by a neuro-reflexive loop originating within the spinal cord.

Similarly, control for bio-morphic explorers could be considered at several levels. At the lowest level is the motion control, including the basic locomotion and articulation. At a higher level, primitive actions such as "move forward" and "turn" are coordinated with sensory input and integrated using an action selection mechanism into more complex behaviors such as "wander around searching for samples while avoiding obstacles". An even higher level of control is the coordination of groups of bio-morphic explorers to achieve mission-level tasks.

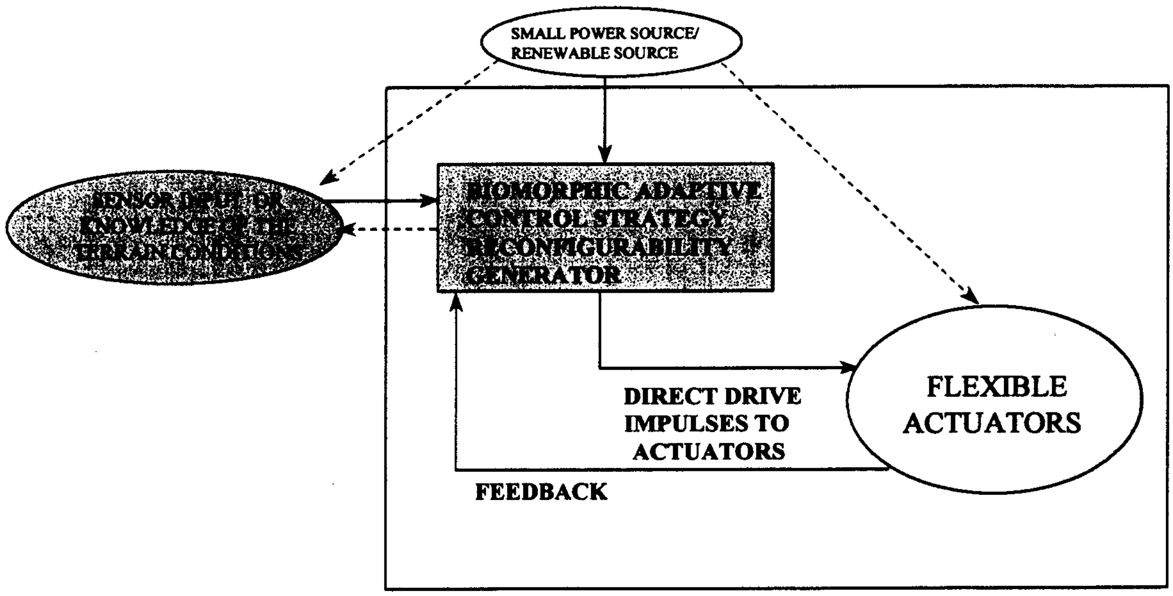

Figure 4: Implementation schematic of bio-morphic explorer

At the lowest level in the hierarchy lies motion control. As illustrated in Figure 4, the knowledge of terrain conditions and real-time sensor input about environment governs earthworm-like robots. Techniques for composing primitive BSR controllers for walkng and jumping into complex, choreographed motions have been developed (using both automated as well as user-directed semi-automated techniques).

A distinguishing feature of the BSR control methodology is that it was designed to be general, to work well with robots whose skeletal structures are describable as articulated figures composed of limbs and joints. The methodology is *not* specific to any particular class of articulated figures (e.g., hexapods), and given a particular bio-morphic explorer, it will be relatively simple to generate BSR controllers for the explorer (the process can be highly automated). This generality will be very useful for reconfigurable bio-morphic robots that can physically reconfigure themselves to adapt to various environmental conditions. In contrast, much of the existing work on biologically-inspired locomotion in robotics (e.g., legged locomotion) is specific to a particular robot, and is difficult to generalize to a large class of bio-morphic shapes.

Figure 5 shows a simulated quadruped[27-29] performing a composite motion consisting of a walk, a turn, and a walk. For this simulation, BSR controllers were generated (using a genetic-algorithm), one for forward locomotion and one for left turns. Initially, the forward locomotion BSR controller is activated. Then, the turn controller is activated, and finally, the forward controller is activated again. This simulation successfully demonstrated:

- the learning of forward locomotion and turn movements using a genetic algorithm, and
- robust, seamless switching in a 3-step sequence consisting of the forward and turn BSR controllers.

5. INNOVATIVE DESIGNS

Figure 6 illustrates an earthworm like robot capturing the peristalsis mechanism for mobility. An application specific design of such a robot could offer a good solution for probing through an earthquake rubble or tunnelling/crawling into cracks in rocks or under rock surfaces. Dedicated sensors such as a miniature active pixel sensor (APS) camera, temperature sensor, or life sensor will form the payload of such an explorer to obtain distributed measurements for scouting the site of interest. Life sensing can be done by looking for carbonates, water, etc. Microspectrometers as small as 3cmx3cmx0.5cm are available from commercial vendors that can be included in the payload to obtain the desired sensing. The front and end segments of the earthworm robot will always perform the mobility function whereas the center segments would 'hold' the payload as needed.

Novel features of the earthworm robot as described elsewhere[30] are:

- Segmented foldable design
- Fault-tolerance, adaptibility
- Flexibility allowing enhanced spatial access
- Reconfigurability allowing adaptibility to terrain

the optimization of coding and representation of the control algorithm. The controller can hence generate outputs that provide actuator shape control (i.e., reconfiguration) as well as control of mobility attributes to adapt to environmental conditions.

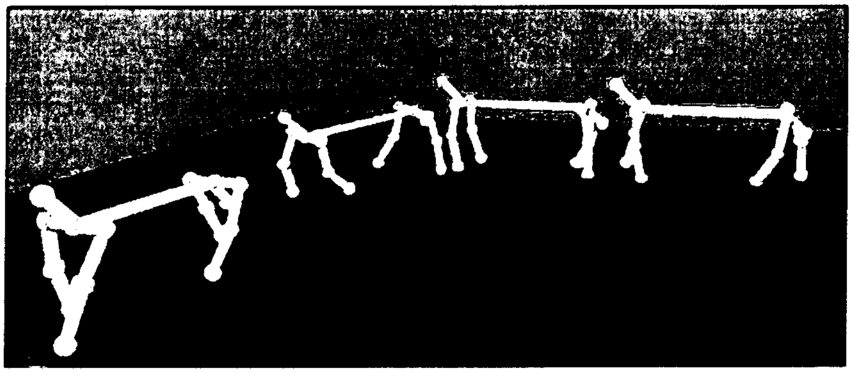

Figure 5: A Simulated Quadruped that Learns a Composite Motion

Motion Control

The use of flexible actuators for mobility poses a control challenge: the coordination of the movement of actuators to achieve desired motions such as locomotion. The desirable characteristics of a control mechanism for bio-morphic explorers include:

1) *Learning*: automatic generation of efficient motions to achieve mobility
2) *Adaptation*: ability to autonomously match terrain and environmental conditions
3) *Fault tolerance*: ability to generate new motions to compensate for possible damage to part of the robot
4) *Composability*: ability to smoothly integrate various primitive motions into complex motions and activities
5) *Generality*: ideally, the mechanism should be general enough so that the control methodology can be applied to a large class of bio-morphic robots.

Recently, there have been significant advances in the real-time, adaptive control of legged robots for mobility. Typically, the control mechanisms used are based on biological principles: a neurally inspired controller (an artificial neural network) is generated using a reinforcement learning.

Banked Stimulus-Response (BSR) Control: a candidate control architecture

Banked Stimulus-Response (BSR), reported earlier by Ngo and Marks[27] and Auslander[28] is a control mechanism that can be applied to bio-morphic explorers, particularly suited for multipod explorers. The BSR control mechanism is a *neurally-inspired* controller which is automatically generated using a stochastic search/optimization algorithm (a variant of a genetic algorithm). It provides a mapping between the current state of the robot (as measured by sense variables such as internal actuator angles, velocity, and internal periodic clocks) and a target internal configuration (configuration of internal actuator angles). BSR controllers have been used to generate motions such as locomotion and jumping for a wide range of simulated robots, including bipeds, quadrupeds, and earthworm-like robots. Techniques for composing primitive BSR controllers for walkng and jumping into complex, choreographed motions have been developed (using both automated as well as user-directed semi-automated techniques).

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- Enhanced spatial access
- Enhanced sample acquisition
- Scaleability
- Reduced complexity/cost
- Surface/subsurface mobility

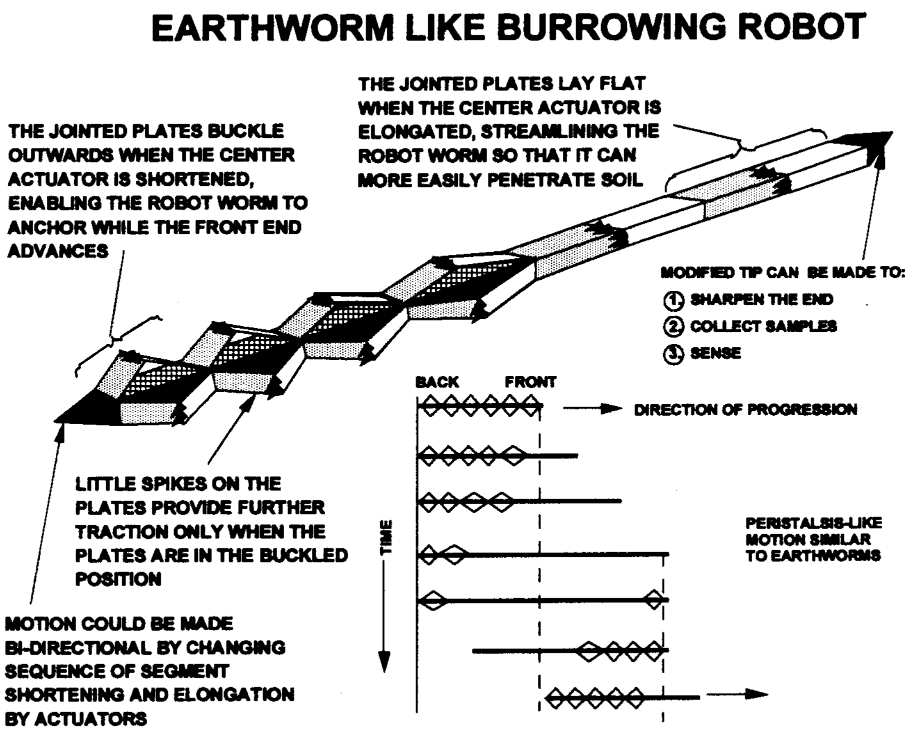

Figure 6: Peristalsis based earthworm-like robot

Taking inspiration from the burrowing techniques of *Amphisbaenia* (as presented by Gans[31]), a design for a subterranean reptile-like flexible penetrator has been created and has been described ealier[32]. The *Amphisbaenia,* a generally leg-less order of reptiles, create tunnels by forcing themselves through the soil. More specifically, they impact the head of the tunnel with their own heads, then compact the soil into the walls of the tunnel. Different species accomplish these actions in different but similar ways. In general, annular rings along the body are expanded against the tunnel's wall, anchoring the animal. A rectilinear motion is then created, culminating in the head striking the head of the tunnel. Once the snout is wedged within the soil, the head is moved back and forth or up and down (keel- or spade-headed species, respectively). This motion compacts the soil in the walls and opens the tunnel so that the animal can move forward. The process is then repeated. The *Amphisbaenia* are a successful order of reptiles that move through the soil in a manner and with an efficiency that conventional mechanical systems cannot. If a rover were created that could mimic the majority of their movement modes, that rover should be able to burrow with an efficiency approaching that of the reptiles.

Overview of the Reptile-like Burrowing Flexible Explorer:

To emulate the behavior of these reptiles requires a mobility system capable of two distinct motions: anchored rectilinear motion and transverse movement of the head and body. The accompanying schematic (figure 7) shows a design composed of a series of modules capable of creating these motions.

- The anchored rectilinear motion is provided by the modules that look like two cones placed base to base. Within these cones is a piston-like assembly, actuated by parallel sets of spring-opposed SMA wires. When the piston is actuated, the outer cone is expanded, providing an anchor in the tunnel walls. Meanwhile, the module's length is decreased. The sketch shows the two rear modules in anchor mode and the three forward modules in extended mode. If the body is anchored by other modules, the release of a particular piston results in the net forward motion of the corresponding module.

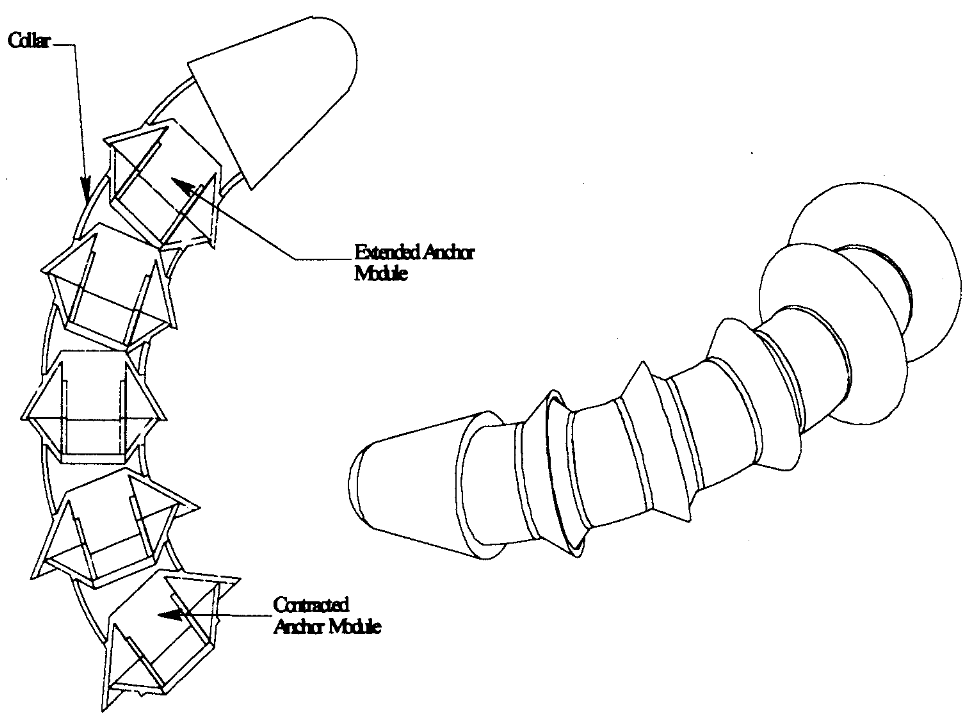

Figure 7: Reptile-Like Flexible Explorer

Connecting the anchor modules are collars of a flexible matrix with embedded SMA wires. These wires are placed longitudinally about the circumference of the collar. As the wires are differentially energized (i.e., just those of the bottom quarter), the collar will have a tendency to bend toward those wires. In this way all or parts of the body can be arched.

<u>Special Issues in the Implementation of this Mobility System</u>

Gans' work provides a blueprint for mobility. In general, the movement will proceed as described above with the gradual lengthening and widening of a tunnel. A troublesome case, however, is the initial entry into the soil. The simplest solution is to burrow into the side of a hill. In this case, the method is the same as for normal burrowing, except the anchor modules can only use the surface soil for resistance. It may be necessary to first dig a starter hole by moving the head into a position normal to the surface by arching the appropriate collars, then pivoting the head about the point of the snout. This movement will eventually displace enough soil that a more normal mode of movement may be used.

Design Refinements

- To decrease frictional losses, all cone surfaces that are directly loaded by the soil should be covered by some Teflon-like coating.
- Depending on the soil conditions and mobility requirements, different head designs could be used. (I.e., a spade-head might be more useful for deep-burrowing rovers as opposed to a keel-head, which might be more useful for in-the-plane steering.

Aqua Worm Variation

A possible design variation that relies primarily on the peristaltic component of motion would be an amphibious worm. Since the general form of locomotion for a peristaltic worm treats soil as a highly viscous liquid, the design could be refined to optimize motion through less viscous fluids such as water. The primary difference would be the inclusion of louvers in the front cone of the anchor modules. These louvers would act as one-way valves through which water could pass as the module moves forward, but which would resist backward motion as the module came into the anchored position. These louvers could either be passive, using the force of the water to close them, or active. Moreover, the front cones themselves would have to be lengthened, providing a larger surface area when in the anchored position. Several other design issues would have to be explored, as well, including the streamlining of the head and modules for hydrodynamic efficiency and the development of a buoyancy system.

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